

A very brief review of Bose-Einstein correlations

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Abstract

The GGLP approach to Bose-Einstein correlations, a hydrodynamic model and a string model are briefly reviewed. The implications of the two models for the Bose-Einstein correlations among the decay products of a pair of W bosons are presented.

1 INTRODUCTION

Several reviews of Bose-Einstein correlations have been recently published [1, 2, 3]. The two reviews published in Physics Reports are each about hundred pages long and are selective. The overlap between them is not large. In order to give a review in the 20 minutes allotted to me, I will have to be very selective. Let me first give three reasons, why the Bose-Einstein correlations are considered to be a good research problem.

Experimentally the effect is spectacular. The experimentalists, coauthors of the seminal paper [4] (further quoted as GGLP) failed to discover the ρ^0 meson. This may seem strange to people used to present day experiments,

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because the ρ^0 is the most conspicuous resonance in the $\pi^+\pi^-$ system, but at that time statistics was not good enough. Nevertheless, the Bose-Einstein correlations were clearly seen. The distributions of the opening angles between the momenta for pairs of like-sign pions ($\pi^+\pi^+$ or $\pi^-\pi^-$) were significantly shifted towards smaller angles as compared to the corresponding distribution for the unlike-sign pions ($\pi^+\pi^-$).

Bose-Einstein correlations in multiple particle production processes give, in principle, access to quantitative information about the structure of the source of hadrons, such as the geometrical size of the source and its shape, the life time of the source, the fraction of this lifetime, when the hadrons are actually being produced etc. There is no other quantitative method of obtaining this information [1].

The problem is hard. At the Marburg conference in 1990, G. Goldhaber, one of the creators of this field of research, said: "What is clear is that we have been working on this effect for thirty years. What is not as clear is that we have come much closer to a precise understanding of the effect". That was Goldhaber's opinion ten years ago. What would be his statement now? What is clear is that he would have changed thirty years to forty years. What is not as clear is that he would have considered any other changes necessary. Whether or not one agrees with Goldhaber that the GGLP paper contains in the nut shell all we understand about the Bose-Einstein correlations, there is no doubt that this is a very important paper and that without knowing the main results contained there it is not possible to discuss Bose-Einstein correlations in multiple particle production processes. Therefore, we will briefly review these results in the following section.

Let us conclude this introduction by a remark on terminology. For some years after the discovery, the Bose-Einstein correlations in multiple particle production processes were known as the GGLP effect. In the seventies it was pointed out by a number of people that the interference of intensities, basic for the GGLP effect, had been used earlier by astronomers to determine the radii of stars. From the names of Hanbury Brown and Twiss, who introduced this method in astronomy, the effect was renamed the HBT effect. This name is still popular, but since the effect results from standard Bose-Einstein statistics, the name BEC, for Bose-Einstein correlations, is now gaining ground.

2 THE GGLP RESULTS

Consider two π^+ -mesons produced one at point \vec{r}_1 , the other at point \vec{r}_2 . Let the momenta of the two pions be \vec{p}_1 and \vec{p}_2 respectively. Suppose first that the two positive pions are distinguishable. Then it makes sense to assume that the pion with momentum \vec{p}_1 originated at \vec{r}_1 and that with momentum \vec{p}_2 at \vec{r}_2 . A reasonable expression for the probability amplitude to observe the two pions at \vec{r} would be

$$A_D = e^{i\phi_1 + i\vec{p}_1 \cdot (\vec{r} - \vec{r}_1)} e^{i\phi_2 + i\vec{p}_2 \cdot (\vec{r} - \vec{r}_2)}. \quad (1)$$

This is the product of two single-particle amplitudes for the two independently produced pions. Each amplitude has a phase, which is the sum of the phase obtained by the pion at birth and of the phase accumulated by the pion in the process of propagation with its momentum from its birth point to point \vec{r} . Since the two pions are identical particles, this amplitude is unacceptable. A reasonable amplitude must be symmetric with respect to exchanges of the two pions. Thus, for two identical pions the amplitude corresponding to amplitude (1) is

$$A = \frac{1}{\sqrt{2}} e^{i(\phi_1 + \phi_2) + i(\vec{p}_1 + \vec{p}_2) \cdot \vec{r}} * \left(e^{-i(\vec{p}_1 \cdot \vec{r}_1 + \vec{p}_2 \cdot \vec{r}_2)} + e^{-i(\vec{p}_2 \cdot \vec{r}_1 + \vec{p}_1 \cdot \vec{r}_2)} \right). \quad (2)$$

The points \vec{r}_1 and \vec{r}_2 are not known, therefore, for comparison with experiment this amplitude should be averaged over some assumed distribution of these points in space. If this is done, nothing interesting is obtained, and here comes the first brilliant idea of GGLP: they assumed that what should be averaged is the squared modulus of this amplitude:

$$|A|^2 = 1 + \cos [(\vec{p}_1 - \vec{p}_2) \cdot (\vec{r}_1 - \vec{r}_2)]. \quad (3)$$

Physically this assumption means that the contributions from various pairs of points (\vec{r}_1, \vec{r}_2) add incoherently. The average

$$\langle |A|^2 \rangle = 1 + \int d^3r_1 d^3r_2 \rho(\vec{r}_1, \vec{r}_2) \cos [(\vec{p}_1 - \vec{p}_2) \cdot (\vec{r}_1 - \vec{r}_2)] \quad (4)$$

depends, of course, on the assumed distribution of the points of origin $\rho(\vec{r}_1, \vec{r}_2)$. GGLP chose

$$\rho(\vec{r}_1, \vec{r}_2) = (2\pi R^2)^{-3} \exp \left[-\frac{r_1^2 + r_2^2}{2R^2} \right], \quad (5)$$

where R is a parameter with the dimension of length, which may be interpreted as the radius of the source of hadrons, and obtained

$$\langle |A|^2 \rangle = 1 + e^{-\vec{q}^2 R^2}, \quad (6)$$

where

$$\vec{q} = \vec{p}_1 - \vec{p}_2. \quad (7)$$

This function of \vec{q}^2 drops from the value two at $\vec{q}^2 = 0$ to values close to one for \vec{q}^2 large. The width of the forward peak is of the order of R^{-2} . Note that these results are qualitatively much more general than the Gaussian Ansatz used by GGLP. For $\vec{q}^2 = 0$ the cosine is equal one and so is its average value. For large values of \vec{q}^2 the cosine is a rapidly oscillating function of $(\vec{r}_1 - \vec{r}_2)$ and its average with any smooth distribution is very small. If the distribution contains only one parameter with dimension of length R , the width of the forward peak must be of order R^{-2} for dimensional reasons. In spite of this generality the GGLP formula for the two-particle distribution is unrealistic. It is certainly not true that the probability of producing a pair of pions depends only on their momentum difference. Here comes the second brilliant idea of GGLP. They noticed that in their model the two particle distribution for distinguishable pions is a constant equal one. Consequently, their result can be reinterpreted as

$$\frac{\rho_2(\vec{p}_1, \vec{p}_2)}{\rho_{2D}(\vec{p}_1, \vec{p}_2)} = 1 + e^{-\vec{q}^2 R^2}, \quad (8)$$

where ρ_2 is the actual distribution of momenta for pairs of identical pions and ρ_{2D} is the corresponding distribution, if there were no Bose-Einstein correlations. The problem is that there is no experiment, where the production of distinguishable π^+ -mesons could be studied and the distribution ρ_{2D} measured. The question how to cope with this difficulty has been extensively discussed without a clear conclusion. For a (pessimistic) review

cf. [5]. GGLP chose to put for ρ_{2D} the distribution for $\pi^+\pi^-$ pairs, where there are (almost) no Bose-Einstein correlations. They found agreement with experiment and derived a plausible value for the radius R .

Since in the GGLP analysis one talks about pions produced at given points with given momenta, it may seem inconsistent with quantum mechanics. This is, however, not the case, because one may obtain the GGLP results starting with the single particle density matrix

$$\rho_1(\vec{p}, \vec{p}') = \langle \vec{p} | \vec{r} \rangle \rho(\vec{r}) \langle \vec{r} | \vec{p}' \rangle, \quad (9)$$

where

$$\rho(\vec{r}) = (2\pi R^2)^{-3/2} \exp \left[-\frac{r^2}{2R^2} \right], \quad (10)$$

which is legal in quantum mechanics, and obtain the two-particle distribution by symmetrizing the product of two such density matrices and taking the diagonal elements

$$\begin{aligned} \rho_2(\vec{p}_1, \vec{p}_2) = & \rho_1(\vec{p}_1, \vec{p}_1) \rho_1(\vec{p}_2, \vec{p}_2) + \\ & \rho_1(\vec{p}_1, \vec{p}_2) \rho_1(\vec{p}_2, \vec{p}_1). \end{aligned} \quad (11)$$

Note that in these formulae ρ_1 is a single particle density matrix, while ρ_2 is a two-particle momentum distribution. The GGLP analysis, nevertheless, has the defect that it leads to ratios (8), which depend only on the difference of momenta, which experimentally is not quite true.

In the following we discuss two more recent models of Bose-Einstein correlations in multiple particle production processes. Both are good and respectable models, but they are based on completely different physical assumptions, which nicely illustrates, how basic are the problems still controversial in this branch of physics.

3 A HYDRODYNAMIC MODEL

A convenient starting point for models of the kind discussed in this section is the source function $S(X, K)$ [6, 7] related to the single particle density matrix by the formula

$$\rho(\vec{p}, \vec{p}') = \int d^4X e^{iqX} S(X, K). \quad (12)$$

In this formula

$$q = p - p' \quad (13)$$

and

$$K = (p + p')/2 \quad (14)$$

are fourvectors. Formula (12) is similar to the well-known formula relating the Wigner function $W(\vec{X}, \vec{K})$ to the density matrix

$$\rho(\vec{p}, \vec{p}') = \int d^3X e^{-i\vec{q} \cdot \vec{X}} W(\vec{X}, \vec{K}). \quad (15)$$

Therefore, the source function is often called a kind of Wigner function, a generalized Wigner function, a pseudo-Wigner function etc. In fact the relation of this function to the Wigner function is rather complicated. One could, of course put

$$S(X, K) = W(\vec{X}, \vec{K}) \delta(X_0), \quad (16)$$

but since there is an infinity of different source functions giving the same density matrix, this is not the only choice. Model builders try to guess a good source function interpreting it as a space time (X), momentum (K) distribution of sources of hadrons. For instance, if the pions are produced by classical sources, one can show [8, 9] that

$$S(X, K) = \int \frac{d^4y}{2(2\pi)^3} e^{-iKy} \langle J^*(X + y/2) J(X - y/2) \rangle, \quad (17)$$

where $\langle \dots \rangle$ denotes averaging over the distributions of sources in various events. Whether the source function is guessed, or derived from some model,

it can be used to find the density matrix in the momentum representation according to formula (12). One should be careful to choose only such source functions, which give distributions of momenta and positions consistent with Heisenberg's uncertainty principle. In practice this usually imposes mild limitations on the parameters of the model.

As an illustrative example let us consider the model described in ref. [1] and in more detail in the references quoted there. The source function is assumed in the form

$$S(X, K) = C m_T \cosh(y - \eta) * \exp \left[- (m_T \cosh y \cosh \eta_t - \frac{x K_T}{r_T} \sinh \eta_t) / T \right] * \exp \left[- \frac{r_T^2}{2 R^2} - \frac{\eta^2}{2 (\Delta \eta)^2} - \frac{(\tau - \tau_0)^2}{2 (\Delta \tau)^2} \right]. \quad (18)$$

This formula is tailored for central collisions of heavy ions. The Z -axis is along the beam direction and includes the centres of the two colliding nuclei. The X axis is chosen so that the momentum \vec{K} is in the Z, X plane. The variables connected to time t and to the longitudinal motion are: the centre of mass rapidity y , the pseudorapidity

$$\eta = \frac{1}{2} \ln \frac{t + z}{t - z} \quad (19)$$

and the longitudinal proper time

$$\tau = \sqrt{t^2 - z^2}. \quad (20)$$

The variables related with the transverse motion are: the transverse component of the momentum vector \vec{K} , $K_T = |\vec{K}_X|$, the transverse mass

$$m_T = \sqrt{m^2 + K_T^2}, \quad (21)$$

the distance from the z -axis $r_T = \sqrt{X^2 + Y^2}$ and the transverse flow rapidity

$$\eta_t(r_T) = \eta_f \frac{r_T}{R}. \quad (22)$$

The free parameters of the model are $C, T, R, \Delta\eta, \Delta\tau, \tau_0$ and η_f . These parameters have simple physical interpretations related to the physical interpretation of the Ansatz (18). The exponent in the third line of formula (18) implies that the particles are produced not too far from the z axis, a typical distance being R , with rapidities not too far from the centre of mass rapidity (chosen as equal zero), a typical rapidity being $\Delta\eta$, and at longitudinal proper time not too far from τ_0 , a typical proper time shift with respect to τ_0 being $\Delta\tau$. The exponential in the second line is a Boltzmann factor, evaluated in the rest frame of a fluid element flowing with longitudinal rapidity y and radially with a transverse rapidity $\eta_t(r)$. T is the temperature and the transverse rapidity is parametrized in terms of the parameter η_f .

This model has been fitted to the data of the NA49 experiment for Pb-Pb central collision at laboratory energy of 158 GeV per nucleon [1]. The results are

$$R \approx 7 \text{ fm}, \quad (23)$$

$$T \approx 130 \text{ MeV}, \quad (24)$$

$$\eta_f \approx 0.35, \quad (25)$$

$$\Delta\eta \approx 1.3, \quad (26)$$

$$\tau_0 \approx 9 \text{ fm}, \quad (27)$$

$$\Delta\tau \approx 1.5 \text{ fm}. \quad (28)$$

Some of these numbers have interesting physical implications. Thus, the radius R is about twice larger than the radius expected from the known size of the lead nucleus. This indicates a significant radial expansion before the hadronization process. The temperature T is lower than temperatures obtained in models used to calculate the chemical composition of the produced hadrons. This may be interpreted as evidence, that the transverse expansion is accompanied by cooling. The value of η_f corresponds to velocities of the order of the sound velocity in a plasma, which confirms that the model is reasonable. The small ratio $\Delta\tau/\tau_0$ indicates that the hadronisation process is short compared to the proper time between the collision and the beginning of hadronization, or freeze out as it is called. This last conclusion should be taken with care, because the authors stress that the value of $\Delta\tau$ is poorly constrained by the data. Thus within a given model it is possible to obtain

much valuable, quantitative information. Much less is known on how model dependent such results are.

A much discussed problem is, whether there should be much difference between the Bose-Einstein correlations for pairs of identical pions produced in the decay of a W boson and for the pairs of identical pions, where each of the pions originates from the decay of a different W boson. Experimentally this is a problem for e^+e^- annihilations in LEP200. Since the experimental situation is not clear it is interesting to know, what are the theoretical predictions of various models. The model discussed in the present section has not been adapted to e^+e^- annihilations, but for any model with a similar philosophy there should be little or no difference between the two kinds of pairs, provided the two W bosons are sufficiently close to each other in ordinary space and in momentum space, which seems to be the case in LEP200.

4 A STRING MODEL

There is a variety of string models. The model discussed here [10, 11, 12] is an extension of the LUND model. It is tailored for e^+e^- annihilations with hadron production. When an electron and a positron collide, usually a quark antiquark pair is first formed. The two partons fly away from each other with the speed of light (we neglect quark masses at this stage). The colour field is confined to a string with the quark at one end and the antiquark at the other. Forming a colour string, however, costs energy. The energy in the string is

$$E = \kappa L, \tag{29}$$

where L is the length of the string and $\kappa \approx 1\text{GeV/fm}$ is a constant known as the string tension. Let us choose the z -axis in the direction of the centre of mass momentum of the quark. Then the antiquark flies in the $-z$ direction and the string stretches (approximately) along the z -axis. At some moment there is no more energy to extend further the string and the directions of flight of the two partons get reversed. There is another interesting possibility. A piece of the string of length δx (away from the ends of the string) can disappear and the energy $\kappa\delta x$ released in the process can be converted into the transverse masses of the quark and antiquark formed at the new ends of the strings. From energy and momentum conservation the two new partons

have equal and opposite transverse momenta related to δx by the relation $\kappa\delta x = 2m_T$. In the language of quantum theory producing such a break means producing two opposite (colour) charges at a distance δx along the z -axis in a uniform force field also along the z axis. The probability decreases rapidly with increasing δx . Therefore, the probability of producing a parton with a transverse momentum k_T also decreases with increasing k_T . One finds

$$P(k_T) \sim \exp\left(-\frac{k_T^2}{2\sigma^2}\right), \quad (30)$$

where σ^2 is a constant of order $\kappa/(2\pi)$. A meson is produced, when a quark and an antiquark forming the ends of a bit of string meet and inherits their transverse momenta. Thus the model explains, why the transverse momenta of hadrons are small.

The description of the longitudinal motion is more complicated. Of great importance is a contour in the z, t plane constructed as follows. One can assume that all the quarks and antiquarks move with the velocity of light $\pm c$ ($c = 1$) and consequently in a (z, t) plot travel along lines making angles of $\pm\pi/4$ with the z -axis. Some move to the right (increasing z), others to the left (decreasing z). Suppose that the original quark moves to the right and up, (increasing time). At some point it turns and begins moving to the left and up. At some other point it meets an antiquark and forms a hadron (this is an oversimplification, but harmless in the present context). The antiquark, however, must have been moving to the right and up, in order to have met the quark moving to the left and up. Following the antiquark line of motion in the opposite direction (or assuming after Feynman that the antiquark moves backward in time) we continue the line from the point, where the hadron was formed, to the point, where the antiquark was formed, i.e. to the point, where the string broke. From this point, we can continue along the line going to the left and up following the quark produced together with our antiquark and reach in this way another point, where a hadron was formed. Continuing this procedure, we can ascribe to each event a closed contour formed of straight sections connecting first the point, where the original quark-antiquark pair was created in the e^+e^- annihilation to the point, where the quark reversed its direction of motion, then from this point to the point, where it hadronized, from this point to the point, where the antiquark involved in the hadronization process was created in a process of

string breaking, from there to the point, where the quark produced in this string breaking process hadronized and so on until we reach the point, where the original antiquark changed its direction and finally again the point, where it had been created in the e^+e^- annihilation. On the (z, t) plane this contour encloses a surface of area A . The crucial assumption is that the probability amplitude for the event is proportional to

$$Ampl(A) = \exp i\xi A, \quad (31)$$

where

$$\xi = \kappa + \frac{ib}{2} \quad (32)$$

is a complex constant. The imaginary part of ξ introduces into the probability of the process the factor

$$|Ampl(A)|^2 = \exp(-bA), \quad (33)$$

which is well known from the standard Lund model. For the description of the Bose-Einstein correlations, however, it is the real part of ξ , which is important. Note that this model, as opposed to the one described in the previous section and in the GGLP approach, does not introduce random phases or explicit assumptions about incoherence. There is no rigorous proof of the basic relation (31), but there are strong plausibility arguments in favour of it [10, 11, 12] — one based on the properties of Wilson loops, and another on the WKB approximation.

In order to evaluate the effects of Bose-Einstein correlations, one proceeds in the standard way. The amplitude for producing n particles with given momenta is replaced by the sum of all the amplitudes differing only by exchanges of identical particles. When two identical particles are exchanged, the contour described above changes. Let us denote the area enclosed by the contour corresponding to the permutation P of the identical particles by A_P . We will further use the notation

$$\Delta A_{PP'} = A_P - A_{P'}. \quad (34)$$

Another effect is that in order to recover the sum zero for the transverse momenta of the two partons produced at each point, where the string breaks, some changes in the transverse momenta must accompany an exchange of

identical particles. We will need the change in the sum of squares of the transverse momenta $(\Delta \sum k_T^2)_{PP'}$. Because of the changes in the area A and in the sum of the squares of transverse momenta, the probability amplitude for the production process changes, when identical particles are permuted. Let us denote the amplitude corresponding to permutation P by M_P , and the total amplitude by M . Then

$$M = \sum_P M_P \quad (35)$$

and the probability of a given final state is proportional to the squared modulus of this amplitude, which can be written in the form

$$|M|^2 = \sum_P |M_P|^2 w_P, \quad (36)$$

where the weight factors

$$w_P = 1 + \sum_{P' \neq P} \frac{2\text{Re}(M_P M_{P'}^*)}{|M_P|^2 + |M_{P'}|^2}. \quad (37)$$

The approximation $w_P = 1$ for all permutations P , corresponds to the case of no Bose-Einstein correlations. In general, using formulae (30) and (31) one finds

$$w_P = 1 + \sum_{P' \neq P} \frac{\cos \frac{\Delta A_{PP'}}{2\kappa}}{\cosh \left(\frac{b\Delta A_{PP'}}{2} + \frac{(\Delta \sum k_T^2)_{PP'}}{4\sigma^2} \right)}. \quad (38)$$

A contribution PP' to the sum on the left is important only, if the change of the area A , when going from permutation P to permutation P' , is not big as compared to b^{-1} . An inspection of the contour shows, that such pairs of permutations differ by exchanges of pairs of particles close to each other along the contour. This in turn are exchanges of particles with production points close to each other and, due to the strong correlation of the production point and momentum in the string model, exchanges of particles with similar momenta. This agrees with GGLP and with experiment: for pairs of identical particles the strongest effect is observed, when the momenta of

the two particles are similar. In general the string picture gives very reasonable results. What is interesting, however, is that it also predicts some new effects, which do not follow from GGLP or from the hydrodynamic picture.

Compare a pair of π^0 mesons and a pair of π^+ meson. In the other models the effect of Bose-Einstein symmetry in the two cases should be similar. The analysis requires some care, as the corrections for Coulomb and strong interactions in the final state are different, but the Bose-Einstein correlations are handled in the same way. In the string model, however, one easily notices, that it is not possible to produce two π^+ mesons next to each other along the contour. More generally, no segment of the contour can contain an exotic combination of hadrons. On the other hand, two π^0 mesons can be produced next to each other. Consequently [11], the effect of Bose-Einstein correlations for $\pi^0\pi^0$ pairs is expected to be stronger than that for $\pi^+\pi^+$ pairs and the effective radius of the hadronization region R calculated from $\pi^0\pi^0$ pairs should be smaller than that for $\pi^+\pi^+$ pairs. These effects are not very strong and the measurements for neutral pions are difficult, so these predictions may take time to be verified, They are, nevertheless, very interesting.

Another remark is about the e^+e^- annihilations, where two W bosons are produced. Such annihilations are being studied at LEP200 and as mentioned in the previous section there is some controversy on the possible difference in the Bose-Einstein correlations between identical pions originating from the same W boson as compared to pions originating from different W bosons. In the string model there is the unambiguous analysis for pairs of identical pions from one string, i.e. from the decay of a single W boson. For pions from two strings, i.e. from two W bosons, this analysis does not apply and another one has not been proposed. In a recent report [13] Andersson suggests that "no cross talk is possible" for pions from different W bosons, which would mean no Bose-Einstein correlations. Of course, nobody doubts that pions are bosons and that their state should have the corresponding symmetry with respect to permutations of identical pions. However, in order to observe the effects associated with the Bose-Einstein correlations since the GGLP paper, besides the Bose-Einstein symmetry certain phase relationships are necessary, and these may be absent for pairs of pions originating from different W bosons. If this string model prediction is taken seriously, it has interesting implications for central heavy ions collisions. In such collisions so many strings are produced that in a purely string picture two identical particles chosen at random are very likely to originate from different strings and con-

sequently would exhibit no Bose-Einstein correlations. Since experimentally the Bose-Einstein correlations in heavy ion collisions are quite strong, this means that the state from which hadronization occurs is very different from a bunch of independent strings.

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